AIAA 95-0633

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Edward L Lin and James W. Stultz
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA

33rd Aerospace Sciences Meeting and Exhibit
January 9-12, 1995 / Reno, NV

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Edward I. Lin[†] and James W. Stultz[‡]
Jet Propulsion Laboratory
California Institute of Technology
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Abstract

The Saturn-bound Cassini spacecraft will be subjected to a high temperature environment at 0.61 AU. Thermal vacuum tests demonstrated that the hybrid Kapton-Mylar MLI layup can withstand an outer layer temperature of 250°C without incurring any damage, and the all Kapton layup, 430°C. The latter will be applied to locales of extremely high temperatures, ti'bile the former more than 85% of the spacecraft's blanketed surfaces. A solar simulator provided a 2.7-sun exposure to the blanket samples; outer layer temperatures of 200°C and 250°C were observed for second surface aluminized Kapton and black Kapton, respectively, which are in line with predictions. The high temperature exposure tests established that current blanket designs will survive the Cassini mission thermal environments with margins.

Introduction

The Cassini spacecraft is currently under development for a mission designed to explore Saturn and its rings, satellites and magnetosphere. The Venus-Venus-Earth-Jupiter Gravity Assist (VVEJGA) trajectory will subject the spacecraft to a 0.61 AU (Astronomical Unit) high-temperature environment at perihelion. Temperatures on some sunlit blanket surfaces at 0.61 AU can reach levels that are beyond the service capability of the conventional Mylar/Dacron net MLI (Multi-Layer Insulation). For example, the RIG (Radioisotope Thermoelectric Generator) shade temperature is predicted to be around 300°C under the combined heating of the RTG (3900 W) and 2.7 suns (i.e., at 0.61 AU) during a trajectory correction maneuver. The main engine blanket temperature can reach 360°C during engine tiring in conjunction with the 0.61 AU solar illumination. The majority of the blanket surfaces, however, will **experience** temperatures with an upper bound of 250"C, since the spacecraft will cruise in the shade of its high gain antenna which is sun-pointed most of the time.

These worst-case hot Cassini Ml.1 temperature predictions are significantly higher than those expected for the Jupiter-bound Galileo spacecraft. During the development of Galileo, several tests were conducted to assess the feasibility of protecting the Mylar/Dacron net MLI with crinkled Kapton layers, to determine the upper temperature limit for Mylar/Dacron net, and to compare the performance of embossed Kapton MLI with that of the Mylar/Dacron net type[1]. The Galileo spacecraft ended up using a mixture of both varieties, either separately or as a hybrid, but with the majority being of the Mylar/Dacron net construction. For Cassini, an MLI layup consisting of 20 layers of embossed Kapton and appropriate outer and inner layers was once considered to be the baseline design, because Kapton can withstand temperatures in excess of 400°C. However, higher cost and inferior thermal performance (i.e., higher effective emittance, as recently confirmed[6]) of the all embossed Kapton MLI relative to Mylar/Dacron net prompted a redirection of the baseline. In the current design, this all embossed Kapton layup, designated the high-temperature layup, will be used only at locations of extremely high temperatures, such as in the vicinity of the RTG and the main engine. A hybrid "standard layup", consisting of 5 layers of embossed Kapton and 15 layers of Mylar/Dacron net with appropriate outer and inner layers, will be used at over 85% of the blanketed surfaces on the spacecraft.

The verification of both layups' capability to meet all thermal requirements has been accomplished by a comprehensive test program which addressed high-temperature survivability, effective emittance, and optical and electrical properties. This paper focuses on the high-temperature exposure tests which helped define the hybrid standard layup, and which demonstrated the adequacy of

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t Member of Technical Staff; Member AIAA both layups in withstanding their respective thermal environments. Two series of high temperature exposure tests were conducted. The first employed a small bell-jar vacuum chamber, in which the MLI samples were tested resting bet ween a hot and a cold plate. Subjected to various boundary conditions, the samples were monitored for their temperatures and visually inspected post-test for damages. The second series of tests employed a larger chamber and a solar simulator which provided a 2.7-sun illumination on the test samples. Transient response and steady state temperature profiles shed light on the behavior of these M LI blankets under solar exposure, during spacecraft trajectory correction maneuvers.

Ibis paper will describe the MLI layup designs, test setups and procedures, and present the test results along with pertinent interpretations.

Description and Abbreviation of MLI Layups

For the sake of clarity and convenience of discussion, the MLI constituents and layups discussed in this paper will be defined and abbreviated as follows:

Constituents:

SSAK: Second surface aluminized Kapton, 1/2 mil thick, ITO(indium tin oxide) -coated on the front, Nomex scrim reinforced on the back, used for outer layer.

BK: Black Kapton, carbon-tilled, 1 mil thick, used for outer layer.

BKn: Same as BK except Nomex scrim reinforced on the back, used for outer layer.

EK: Embossed Kapton, 1/3 mil thick, aluminized on both sides, used for intermediate layer.

MN: Mylar with Dacron net, alternating layers; 1/4 mil thick Mylar aluminized on both sides, used for intermediate layer.

AK: Aluminized Kapton, 1 mil thick, aluminized on both sides, used for inner layer.

Layups:

Standard Layup: A blanket assembly consisting of layers SSAK -t 5EK + 15MN -t AK; to be used on more than 85% of the blanketed surfaces on Cassini.

High-Temperature Layup: A blanket assembly consisting of layers BK -t 20EK -t AK; to be used at high temperature locales.

Temperature Limits for MLI Constituents/Layups

Temperature limits for various MI,1 constituents and layups are first reviewed for background information and for focusing attention on areas of vulnerability. Based on manufacturers' information and data from past test programs, "weak links" in several blanket layups are identified. Table 1 summarizes the key data pertinent to Cassini applications. The temperature data are obtained from Refs. 1 -5. Several tests conducted in the past for the Galileo Project had converged to an assessment' that the maximum allowable temperature for Mylar/Dacron net is 220°C, which is in line with the melting point and zero strength temperatures for these materials as indicated in Table 1, For the SSAK and BKn outer layers, both the Kapton substrate and the Nomex scrim reinforcement have high temperature capability, and the 3P adhesive (a polyester, polyimide and polyamide blend) is the weak link. Hence, in terms of the layups listed in Table 1, the limiting constituent for layups 1 and 2 is the 3P adhesive, and that for layups 3 and 4 is the Mylar/Dacron net. Further, it is clear from Table 1, as well as from numerous past experiences, that cold temperatures of outer space are of no concern for these layups.

Table 1. Temperature Limits for Ml.] Blanket Constituents and Layups

Constituent	Melting Point (°C)	Zero Strength Temp (°C)	Field Service Temp (°C)
Kapton film	None	815	-269 to 4400
Mylar film	250	248	-60 to +150
Teflon film	327	310	
Dacron net	256	245	
Nomex scrim	427		
Glass scrim	>400		
Adhesive			
3P			max 200-260
Acrylic			max 120
Silicone			max 150

Layup	Allowable Temperature Range (°C) Continuous	Intermittent
1. SSAK+EK	-184 to + 149	-184 to +260
2. BKn+EK	-184 to +149	-184 to +260
3. SSAK+MN	-251 to + 121	max 220
4. BKn+MN	-251 to -t 121	max 220
5. BK+EK	-251 to -t 288	-251 to +399

Data Sources: DuPont I'ethnical Information Bulletins; Sheldahl Red Book, Rev. 7/89; and past JPL tests.

The Bell-Jar Tests

Test Objectives

The objectives of these tests were to verify that both the standard and high-temperature layups can survive the 0.61 AU thermal environment, and to determine the number of embossed Kapton layers necessary to protect the Mylar/Dacron net layers.

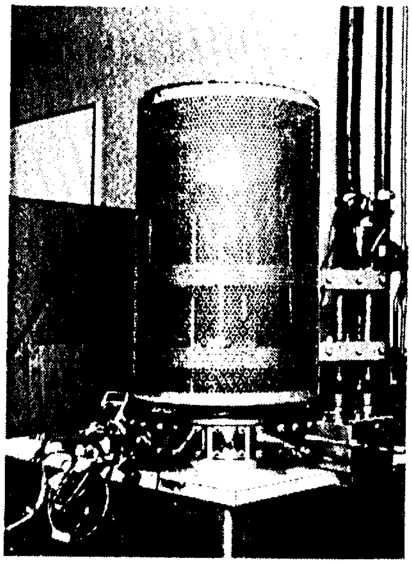

Fig. 1 The Bell-Jar Vacuum Chamber

Test Article, Setup and Procedure

The bell-jar vacuum chamber has a height of 0.91 m, and a diameter of 0.46 m, approximately (Fig. 1). It housed a test assembly that consisted of a hot plate on the top, a cold plate at the bottom, and an MLI blanket sample sandwiched between the two, as shown in Fig. 2. All three are of approximate dimensions 0.3 m x 0.3 m, and with truncated corners. The aluminum hot plate was 0.64 cm thick, painted black on the bottom side, equipped with three Chromalox strip heaters, and suspended from a stand. The copper cold plate was roughly 0.16 cm thick, painted black on the top side, fitted with serpentine copper tubing to circulate coolant, and was supported with four short struts from the floor of the chamber. The electric strip heaters were made of chrome steel sheath, each capable of dissipating 400 W and sustaining 650°C.

The space between the hot and cold plates was adjustable, allowing the MLI sample to rest freely on the cold plate. Three MLI blanket samples were tested: (A) the standard layup; (B) a layup consisting of SSAK + 10EK + 15 MN + AK, to investigate the effects of

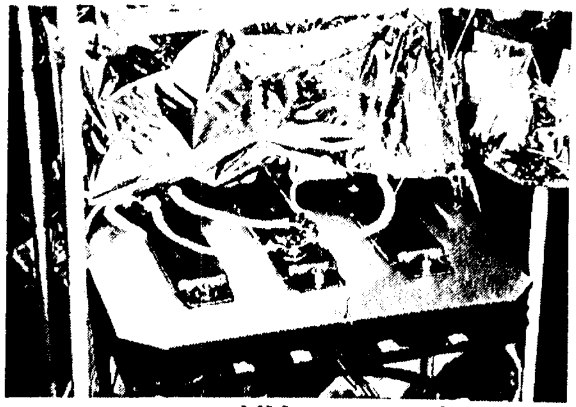

Fig. 2 The Hot Plate, MLI Sample and Cold Plate

the additional 5 layers of embossed Kapton; and (C) the high-temperature layup. The MLI sample typically appeared as shown in Fig. 3, with thermocouples mounted in the center region of various layers. The blankets were only partially seamed, so as to allow thermocouple attachment/removal and post-test inspection. The thermocouples were of Type E (Chromel constantan), gage 30, and with either Teflon or fiberglass wrapping, the latter being reserved for higher-temperature locations.

Fig. 3 MLI Test Sample with Thermocouples

For a typical test run, after the MLI sample is properly installed, the hot plate was covered on top and the test assembly surrounded along the periphery by MLI blankets to prevent heat loss (Fig. 4). Heat was driven from the hot to the cold plate through the MLI sample in a predominantly unidirectional flow. The intent was to heat the hot plate to the point that the top layer of the MLI blanket could be maintained at the target level (250°C for the standard layup, and above 350°C for the high-temperature layup). For most test runs, the cold plate was kept at about 15°C by the circulating tap water. However, film heaters were mounted on the cold plate so that on occasions, the plate could be controlled to a higher temperature to simulate a warm hardware surface.

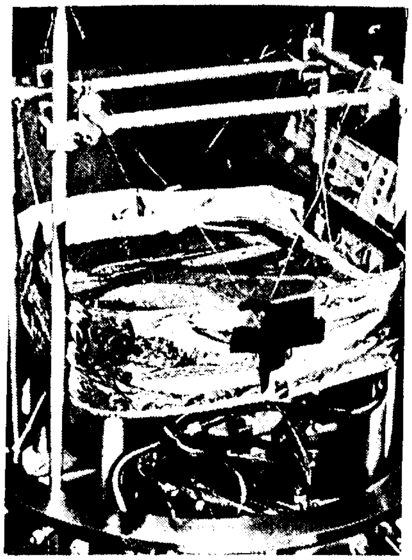

Fig. 4 The Test Assembly

The chamber pressure during a test ranged from 1 x 10^{-4} to 4x 10“s torr. Test conditions were held constant for several hours once steady state was approached. Upon completion of the test, the chamber was opened, and the MLI sample inspected. Temperature, power and pressure data were recorded by a data logger.

Results

The standard layup was tested under the conditions with the hot plate at 254°C and the cold plate at 14°C and 46°C, respectively. The steady state temperature profiles across the blanket layers during the 3 to 4 hours of exposure are shown in Fig. 5. The two lower curves which almost coincide with each other were obtained from tests done with the same boundary conditions on two different days, with a chamber break and blanket inspection in between; reproducibility of the test results is good. The upper curve was obtained with a warmer cold plate temperature (46°C) to simulate a warm hardware condition. The top Mylar layer temperature is seen to be below 185°C in all three cases, which is well below the limit of 220°C for Mylar. Considering that the outer layer temperature in flight is predicted to be under 200°C for all but the high-temperature locales on the spacecraft, these results indicate that the standard layup possesses a substantial margin as far as high temperature survivability is concerned. In addition, inspection of the blanket sample following each of the three tests revealed no visible damage. The white polyester tape along the edges of the blanket turned brown; this is attributed primarily to outgassing from the aged thermocouple wrapping, which will not be present in flight. Also, Mylar shrinkage appeared to be 0.64 cm out of 30.S cm, or 2%, confirming manufacturer’s data and previous test results.

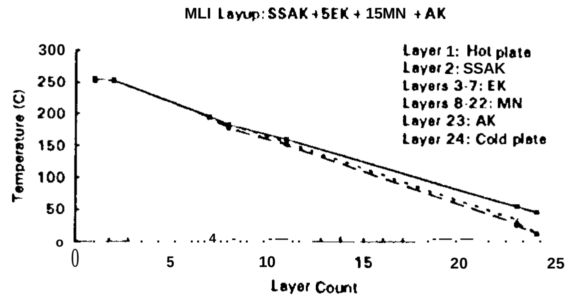

Fig. 5 Steady State Temperature Profiles Across the Standard Layup

Figure 6 presents the test results that illustrate the effects of adding five layers of embossed Kapton. A comparison of Figs. 5 and 6 indicates that the temperature of the top Mylar layer is reduced by 40°C as a result (i.e., from 180 to 140°C). This is a significant gain in terms of added protection to the Mylar layers, and can be exploited where beneficial. However, for most Cassini applications, the standard layup is adequate with the substantial margins already demonstrated,

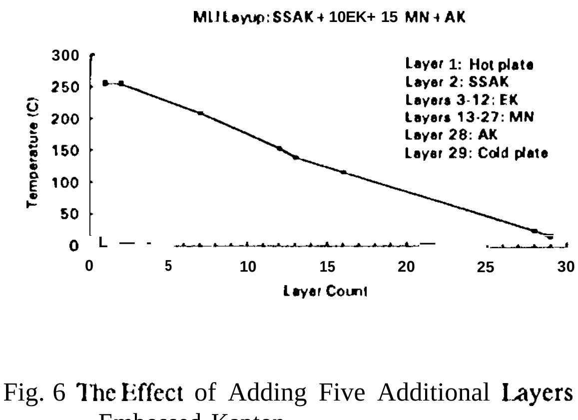

Fig. 6 The Effect of Adding Five Additional Layers of Embossed Kapton

The high-temperature layup was tested with the cold plate maintained at around 15°C and the hot plate at 357°C and 431 °C, respectively. The steady state temperature profiles are presented in Fig. 7. It is obvious that these temperature levels are well within the capability of the Kapton films. Furthermore, post-test inspections revealed no visible damage. After two hours of exposure at these steady temperatures, the black Kapton outer layer still appeared intact, smooth and shiny. All the embossed Kapton layers with the raised embossed patterns were intact; the annealing, i.e., flattening out, of crinkled Kapton layers observed at high temperatures in past tests did not occur here.

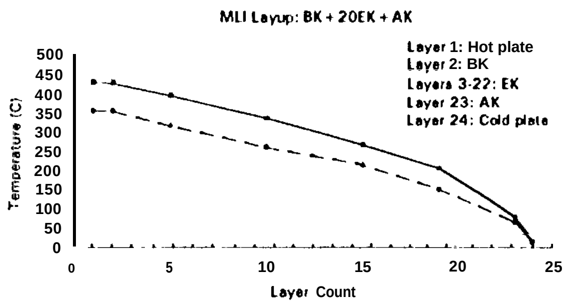

Fig. 7 Steady State Temperature Profiles Across the High-Temperature Layup

It is worthwhile to note the following by-product information which also resulted from the tests: (1) The strip heater temperatures during the last test ranged between 460°C and 520°C, and five layers in the central region of the cover blanket (i.e., that which covered the top of the hot plate and hence in partial contact with the strip heaters) were completely disintegrated into ashes. The cover blanket was made of aluminized and embossed Kapton layers. This illustrated the destructibility of Kapton at temperatures somewhere above 430"C. (2) The skirt blanket around the test assembly was of the Mylar/Dacron net construction. The inside layers were melted through at several places. Although there were no temperature measurements made, this serves to indicate the destructibility of Mylar and the manner of its destruction. (3) Severe outgassing took place especially during the last test when the temperatures were the highest. Gluey, dark brown deposits occurred in large amount along the edges of the cold plate and the MLI sample, and on the cold water tubing, the skirt blanket, and other cold spots. In contrast, all the hot surfaces were clean. The sources of outgassing included the adhesives, the brown Kapton tape, the thermocouple wrapping, and others, most of which are not expected to be present in flight. This serves to underscore the importance of outgassing considerations in blanket materials selection, especially in high temperature regions.

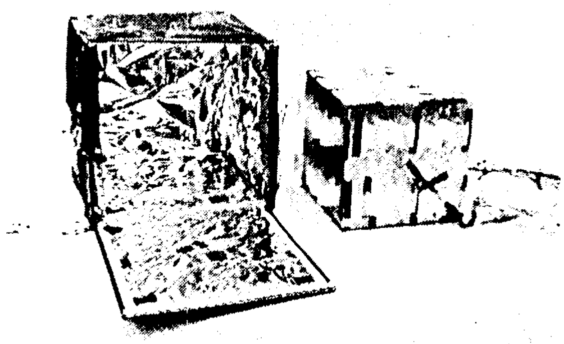

Fig. 8 MLI Sample and the Aluminum Box with Mylar Standoffs

Solar **Simulator Tests**

Test Objectives

The objectives of these tests were to determine the response of the standard layup and the high-temperature layup under the 2.7-sun illumination by a solar simulator, and to verify that the blankets can withstand the 2.7-sun exposure for at least 30 minutes, corroborating the bell-jar tests.

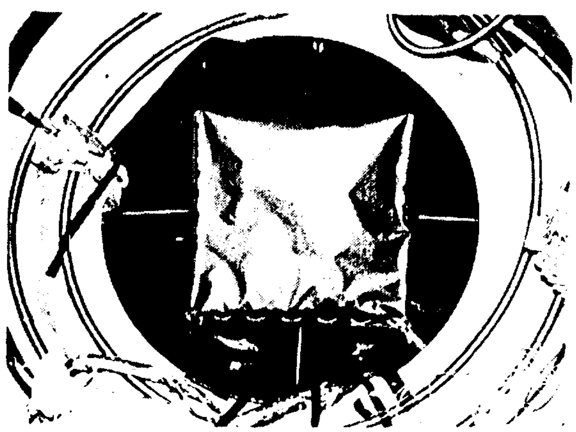

Fig. 9 MLI Test Article Suspended in the Vacuum Chamber

Test Article, Setup and Procedure

The solar exposure tests were performed on the heels of a series of tests that were designed to determine the effective emittance of the MLI layups. The latter results will be reported elsewhere. The MLI blankets were tested wrapping around a 0.23 m cubed aluminum box that was heated from within. The box was made of 0.32 cm thick Aluminum 6061-T6 plates, painted black on the inside, and with film heaters and thermocouples mounted on the inside that can heat and control the box to near uniform temperature at various levels. Two MLI layups were tested; i.e., the standard and the high-temperature layups, as described before. The MLI test samples were instrumented with thermocouples at selected locations, and at various layers on the side that was to be illuminated by the solar simulator. Figure 8 shows an MLI sample and the box. The box had Mylar standoffs (3.8 cm high) attached on all surfaces; the standoffs space off the blankets which serves a micrometeoroid protection requirement.

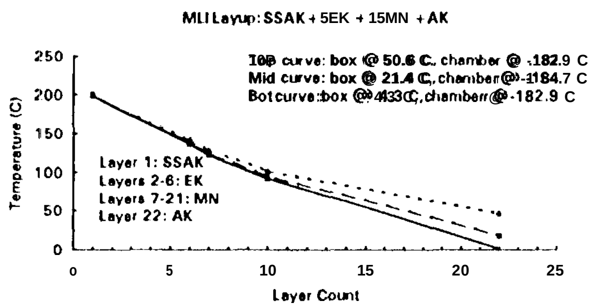

Fig. 10 Steady State Temperature Profiles Across the Standard Layup Under 2.7-Sun Illumination

The tests were done in a 91-cm diameter, LN_2-cooled vacuum chamber located in the JPL environmental test facilities. Figure 9 shows the assembled test article suspended in the chamber with an annular door shroud that allowed through the light beams coming from the solar simulator. The solar simulator was a SpectroLab product, Mark III X25, calibrated to provide 3675 W/m^2 of irradiance (i.e., 2.7 suns) on the illuminated blanket surface. The chamber was cooled to below -180°C, and the pressure maintained at low to high 10^{-7} torr during the tests. Typically, when these conditions were reached, the solar simulator was turned on. Power input to the box was adjusted, and temperatures at the box as well as all the blanket layers were monitored. After steady state was attained and held for at least one or two hours, the test was terminated. Steady state was operationally defined as a state when all temperatures changed at a rate of less than 0.3°C/hr. Upon completion of the test, at chamber break, the test article was removed from the chamber, disassembled, and inspected visually to determine if damages or changes had occurred.

Results

When the solar simulator was turned on, the outer layer temperature changed almost instantaneously, while the innermost layers took up to an hour to respond. This implies that for trajectory correction maneuvers that last no longer than 30 minutes, no thermal effect from solar exposure on blanketed hardware should be expected. The steady state temperature profiles across layers of the illuminated blanket typically decrease monotonically toward the hardware. Figure 10 shows the results from three tests that were conducted with the standard layup. The three tests differed principally in the box temperatures, which turned out to affect only the inner layer temperatures. The SSAK outer layer temperature of 200°C is somewhat higher than predicted for a blanket surface viewing the outer space exclusively, because during the test, the blanket viewed the cold annular door shroud as well as the warmer quartz window (estimated to be 40°C to 60°C on the average). However, for blanket surfaces that also view other parts of the spacecraft, the temperature of 200°C may not be too far removed from reality. The important point, however, is that Fig. 10 indicates that both the Mylar and Kapton layers will be able to survive the 2.7-sun illumination at 0.61 AU, with substantial margins (i.e., in excess of 80°C). Again, post-test inspection revealed no visible damage to any layer.

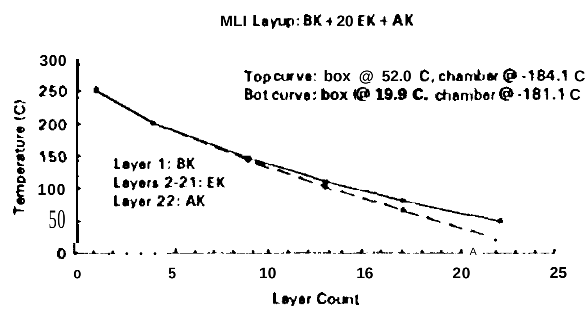

Fig. 11 Steady State Temperature Profiles **Across the** High Temperature Layup Under 2.7-Sun Illumination

Steady state temperature profiles for the high temperature layup under solar illumination are displayed in Fig. 11. The Black Kapton outer layer temperature is 250°C, and the underlying embossed Kapton layers have monotonically decreasing temperatures toward the box. The 250°C is somewhat higher than predicted for a totally space-viewing blanket, but is significantly lower than if the additional heat source of the RTG or main engine is applied.

Absorptivity and Emissivity of Outer Layers

The absorptivity and emissivity of the outer layers (SSAK and BK) were measured before and after the solar exposure. They are presented in Table 2 under the headings "virgin sample" and "exposed sample", the latter meaning after 8 hours of cumulated exposure to 2.7 suns. It is clear that the exposure caused appreciable changes to the SSAK, but almost no change to the BK.

Table 2. Optical Properties Before and After Solar Exposure

Outer Layer Mat'l	Virgin Sample		Exposed Sample	
	α_s	ϵ_h	α_s	ϵ_h
SSAK	0.29	0.66	0.34	0.51
BK	0.92	0.81	0.92	0.80

Conclusions

The standard and high-temperature MLI layups being baselined for the Cassini spacecraft have been described, They have been subjected to two series of tests to ascertain their high temperature survivability. The bell-jar series of tests demonstrated that the standard layup is capable of withstanding an outer layer temperature of 250°C, and the high-temperature layup, 430°C. No visible damage occurred to either blanket and all layer temperatures were well within the allowable limits for the constituent materials. The five embossed Kapton layers in the standard layup was shown to provide adequate protection for the fifteen underlying Mylar/Dacron net layers; the top Mylar layer temperature was 180°C, substantially below the material limit of 220°C, even with the conservative outer layer temperature,

The solar simulator series of tests demonstrated that both layups can survive the 2.7-sun exposure. Under the simulated O.61 AU conditions, the SSAK outer layer attained a temperature of 200°C, and the BK outer layer, 250°C. These temperatures, although somewhat conservative due to the warm quartz window the outer layers viewed during the tests, are in line with calculations based on a realistic range of absorptivity and emissivity values for the materials. The two series of tests corroborate to establish that both layups will be able to survive, with substantial margins, the severest high temperature environments that the Cassini mission will present.

Acknowledgment

The authors wish to thank R. Reeve for the various technical discussions held throughout the test phases. The successful completion of these tests would not have been possible without the efforts of the following contributors: J. Real for fabricating and installing the blankets; W. Walker for assisting with the bell-jar tests; R. Okarnoto and the Building 18 personnel for fabricating test fixtures; A. Burrows, P. Martin, G, Laugen and their assistants for operating the vacuum chamber and solar simulator; L. Johnson and H. Winter for fabricating thermocouples; T. Fisher, E. Bailey and D. Perry for data acquisition; and P. Stevens for measuring optical properties.

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